Meteorological Studies with the Phased Array Weather Radar and Data Assimilation Using the Ensemble Kalman Filter

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14. ABSTRACT
The long-term goal of this project is to integrate two state-of-the-art technologies, the phased array weather radar (PAR) and the emerging Ensemble Kalman Filter (EnKF) data assimilation method, to optimize the radar performance and improve coastal and marine numerical weather prediction (NWP).

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LONG-TERM GOALS

The long-term goal of this project is to integrate two state-of-the-art technologies, the phased array weather radar (PAR) and the emerging Ensemble Kalman Filter (EnKF) data assimilation method, to optimize the radar performance and improve coastal and marine numerical weather prediction (NWP).

OBJECTIVES

This project leverages on the new PAR in Norman, Oklahoma to exploit phased array technology and its applications to improve NWP through EnKF data assimilation with the goal of improving environmental characterization and forecast to optimize naval operation. This project will further enhance the existing collaboration among ONR, National Serve Storms Laboratory (NSSL), and the University of Oklahoma (OU) to achieve the four specific research objectives: (1) develop an EnKF framework for optimally assimilating quantitative observations of the atmosphere including the PAR data, (2) design a sophisticated radar emulator which will be used to validate innovative processing techniques developed in the project and to design accurate and efficient forward observation operators for assimilating PAR data, (3) advance phased array radar technology through the development of novel signal processing techniques and integration of current state-of-the-art technologies to provide high-quality and high-resolution weather measurements, and (4) evaluate the impact of scanning strategies including SPY-1 tactical and non-tactical waveforms on data assimilation and NWP using the Observing System Simulation Experiments (OSSE) and Observing System Experiments (OSE). Optimal scanning strategies of PAR for NWP model initialization will be developed and tested.

APPROACH

Our multidisciplinary team is comprised of scientists with academic and industrial expertise in radar engineering, radar signal processing, EnKF data assimilation, numerical modeling, and weather prediction. Our approach is to exploit these complementary talents to achieve the goals of the proposed research. The five main research thrusts are discussed in the following.

(1) **Design of the PAR Emulator**: A sophisticated PAR emulator is designed to take in high-resolution three-dimensional meteorological fields and to generate synthetic radar time series data. The output of the emulator is then processed to produce the three spectral moments (reflectivity, mean radial velocity and spectrum width). The emulator is flexible enough to produce radar data for various waveforms, sensitivity, and sectoring. The emulator will serve as a vehicle for developing accurate and efficient forward observation operators for PAR data assimilation. Moreover, error characterization can be obtained in the emulation and will be fed into the EnKF system.

(2) **Establish the EnKF system**: The existing EnKF-based OSSE framework for radar data developed by our group will be extended (a) to use much more realistic, yet efficient, forward observation operators that will be derived from the full-scale PAR emulator discussed in (1), (b) to handle PAR data collected in various non-conventional manner such as angular oversampling, and (c) to effectively account for model errors. The availability of an accurate and realistic radar emulator will allow us and the Navy to evaluate the impact of various simplifications (needed for efficient) in the observation operator on the quality of analysis and the subsequent forecast.

(3) **Technology Innovation**: This research thrust focuses on the exploration of phased array technology merged with novel signal processing techniques. An agile beam phased array radar has the potential to not only increase the scanning rate, but also to measure meteorological variables not currently available and to enhance data quality. For example, a novel scanning scheme termed beam multiplexing (BMX) is developed to optimize the scan time and data quality. In addition, the refractivity on surface, which can serve as a proxy of humidity, can be measured from the radar returns from ground clutter. The impact of these technology innovations on numerical prediction can be evaluated and quantified using the OSSE and OSE.

(4) **Observing System Simulation Experiment (OSSE):** A comprehensive simulation system is being designed to integrate the processes of designing radar scanning strategies, making observations, assimilating data, and producing forecasts with the goal of improving short-term weather prediction and better understanding the relationships among all involved processes. The SPY-1 waveform with 1-pulse (reflectivity only) in clear mode, 3- or 4-pulse in Moving Target Indicator (MTI) mode, 16-pulse, and 32-pulse will be simulated and their impact on data assimilation and weather forecasting will be evaluated and quantified. Moreover, a framework for developing an optimal scanning strategy is being established based on a feedback design in the simulation. In other words, the information of the difference between the forecast and high-resolution model outputs can be used to adjust scanning patterns until optimal results are achieved.

(5) **Data Collection and Observing System Experiments (OSE):** The findings and lessons learned through radar emulator and OSSEs will then be demonstrated using the PAR at NWRT. Various scanning strategies tested with the OSSEs will be implemented with the PAR. We will leverage on a suite of existing weather radars including the research NEXRAD (KOUN), the mobile SMART radars, the nearby operational NEXRAD (KTLX) radar to validate the PAR measurements and retrieved variables.

WORK COMPLETED

The team has been continuously working toward project goals. The following specific tasks are completed in 2009.

(1) **Refining the Application of EnKF to Real Data**: The major effort of EnKF system this year has been focusing on the evaluation and refinement of the multiscale scheme/procedure that was used in the benchmark experiment of May 8 2008, OKC supercell case. It is highlighted that multiscale complexity is an important issue for EnKF when real radar data are used. The multiscale analysis scheme developed in this project provides a method to address this issue. The proper use of high-resolution surface data in EnKF has been further studied. To account for model errors to improve sampling ensembles representation of forecast errors, multiplicative, additive inflation methods and perturbed microphysical interception parameters have been implemented and evaluated in this benchmark real case. A manuscript on this topic, titled "Multi-scale analysis and prediction of the 8 May 2003 Oklahoma City tornadic supercell storm assimilating radar and surface network data using EnKF" has been prepared and will be submitted to the Monthly Weather Review soon.

(2) **Study of Spatially Inhomogeneous and Scanning-dependent Radar Errors**: One of the ongoing efforts for improving convective-storm analysis and prediction is to assimilate the PAR

data into the Advanced Regional Prediction System (ARPS) using EnKF. This procedure has been recently enhanced to use proper beam pattern and range weighting functions to assimilate radar data on a radial-by-radial basis. The earlier OSSEs have been extended to examine additional capabilities of the PAR in more realistic settings this year. Confirming earlier results, azimuthal over-sampling and rapid update time are shown to improve the analysis. For these experiments, observation errors that are spatially inhomogeneous and scanning strategy-dependent were applied. By properly modeling the expected error in the observations for different scanning strategies, the results of the OSSEs become more robust.

(3) **Using Time Balance Scheduling for Adaptive Weather Sensing**: The WSR-88D typically scans a volumetric region with an update time of 4-5 min. All the storms of interest are updated at the same rate. It is desirable for multi-function PAR weather radar to scan multiple storms with different and fast update times without degrading data accuracy, while surveillance is still maintained to ensure the detection of newly developed storms. Nevertheless, all these tasks are competing for radar resources. A scheduling algorithm based on the idea of time balance (TB) was developed and verified for scheduling multiple tasks for adaptive weather sensing. Two radar functions, storm tracking and surveillance, are of interest to perform adaptive sensing. Two quality measures of revisit improvement factor and acquisition time were defined to quantify the trade-offs for such adaptive scanning strategies. To demonstrate the performance of TB scheduling and its impact on the two quality measures, simulations based on interpolation of real WSR-88D data to a finer time scale were conducted.

RESULTS

The results are highlighted in the following three areas.

(1) Application of ARPS EnKF to a Tornadic Supercell on May 8, 2003

The team has continuously working on this case and a number of modifications have been made. A modified schematic diagram is shown in Figure 1 to exemplify the multiscale analysis in a benchmark experiment of the May 8 2003 case.

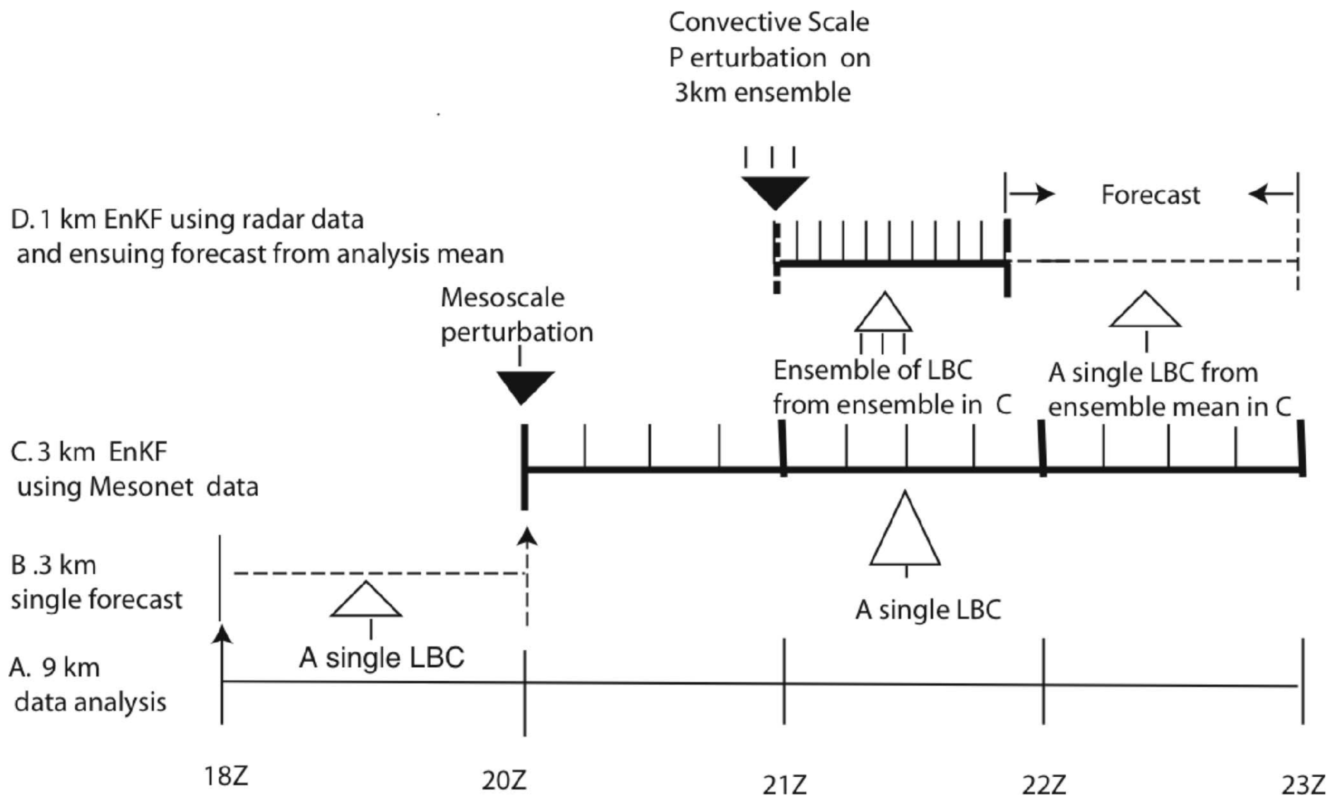

Fig.1, Schematic diagram of the multiscale approach used in the benchmark experiment. From bottom to top, the single 9 km control run in A is the ARPS simulation with initial and lateral boundary conditions (LBC) from Eta. At each hour, the available sounding and surface data are analyzed by the ARPS 3DVARsystem. The 3 km forecast of B from 1800 UTC is initialized from ARPS 3DVAR of available surface observation and interpolated 9 km run as the background. The 9 km run also provides lateral boundary conditions for the 3 km forecast of B, which will be used as the first guess for initial ensemble on 3 km resolution in C.

In this work, it is noted that for the application of EnKF to real data, the complexity associated with interactive multiscale atmospheric processes relevant to storm initiations triggered by the mesoscale processes plays an important role. The multiscale analysis provides a method to address this issue and is demonstrated through its successful application in the benchmark case. Sensitivity experiments also show that the performance strongly depends on the representation of storm initiation by using 3DVAR analysis (A and B in Fig. 1) as a sub-system in this multiscale analysis. In addition, experiments show that the surface observation operator still needs to be improved. In the present run, only wind observations at 10 m height is used, while the lowest level in the model is set at 10 m and only horizontal interpolation is used in the observation operator. The forecasted storm propagates in agreement with real radar observation very well, as shown in Fig. 2.

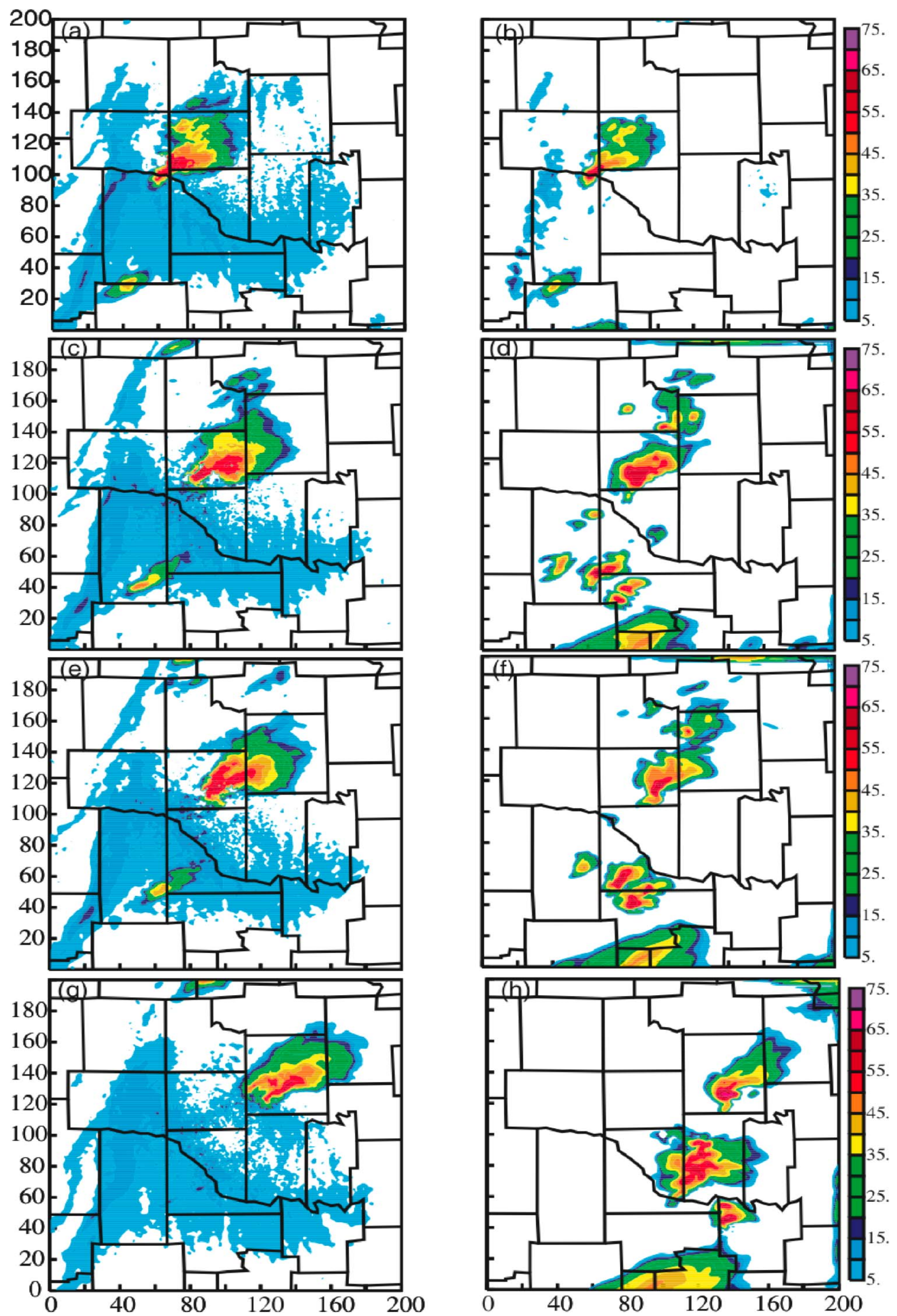

Fig. 2 Reflectivity at 0.45° elevation angle in 1 km domain D2 with coordinate in kilometer at 2155, 2220, 2230 and 2300 UTC from top to bottom, respectively. The left column is for observations by the KTLX from the four selected times. The right column shows projections from the ensemble analysis mean (b) and subsequent forecast in (d), (f) and (h) in the control run (where both KTLX and KFDR radars are used). Although the forecasted and observed main storms are consistent, it is also noted that the forecasted storms on the southwest of the main storm did decay as observed one.

To account for model error and improve EnKF using radar data, multiplicative and additive errors and the method of perturbed microphysical interception parameters were implemented in the ARPS EnKF system. The results indicate that for the benchmark case, such methods of incorporating errors are prone to cause spurious structures and/or smoother realistic fine structures associated with low level hook echo in the forecast. A comprehensive investigation is needed to understand this issue.

(2) **Study of Spatially Inhomogeneous and Scanning-dependent Radar Errors**

Our preliminary study is to enhance OSSEs with ARPS EnKF by incorporating realistic radar errors, which depend on the scanning strategy and true reflectivity (signal strength). For OSSEs, radar data with observational errors was typically simulated by adding random noise with a uniform standard deviation to the error-free observation that was estimated using the state variables from the output of numerical model. Although the reflectivity error is typically added in log domain, the error model has been extended to add error in a linear domain. Furthermore, the error estimation has been developed to be spatially inhomogeneous and scanning strategy-dependent. Specifically, the observation error is a function of the strength of radar return, number of pulses, and pulse repletion time. The impact of scanning strategies including oversampling was re-examined using the more realistic error model and is demonstrated in Fig. 3. It is assumed that PAR and WSR-88D have the beamwidth of 2^{o} and 1^{o}, respectively. It is shown in (a) that PAR oversampling with 1 or 0.5 degrees increment show better performance than WSR-88D that has 1 degree beam width without oversampling, when the storm is located far from the radar and data is assimilated every 5 minutes. On the other hand, if the storm is located close to the radar, the improvement provided by oversampling is not obvious, as shown in (b). For this case, conventional scanning using WSR-88D shows the best performance. It suggests that the PAR should mimic the WSR-88D's scanning pattern for this case. When radar data assimilated in a shorter cycle (every 2 minutes), RMS errors are reduced much more rapidly than the one with longer cycle as shown in (c). However, the RMS errors reach the lower limit faster if the storm is located far from radar. Generally speaking, observations with fast updates can be achieved using fewer sampling, which leads to the degradation of data accuracy. However, PAR can adaptively scan multiple regions of interest and provide rapidly updated observation by electronically beam steering. This capability allows fast updates of weather information without comprising data accuracy. When the scanning strategies are taken into account for error estimation, conventional scanning pattern by WSR-88D shows worse result than PAR oversampling as shown in (c). On the other hand, WSR-88D's scanning pattern shows as good performance as PAR oversampling as shown in (d) when the error is scanning strategy independent.

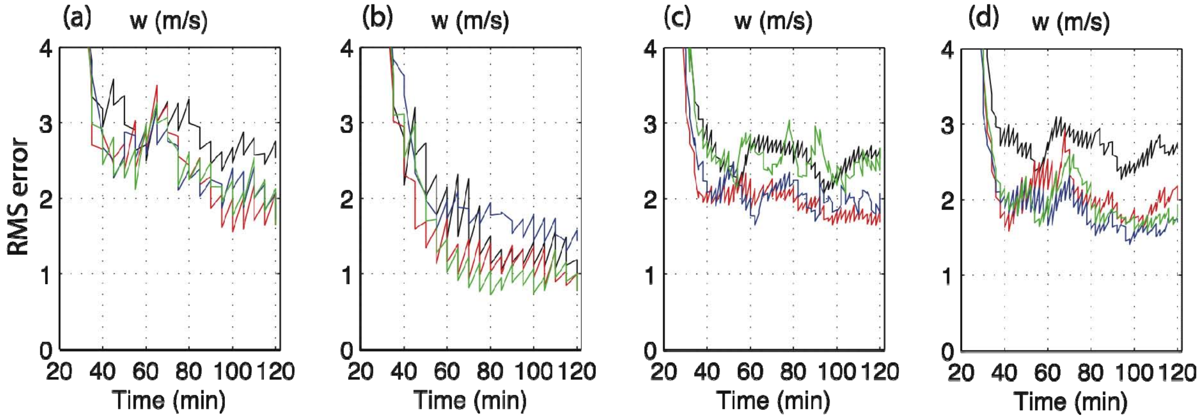

Fig. 3, Ensemble-mean forecast and analysis of RMS errors for vertical velocity w. For (a), radar location and assimilation cycle are (-100, 0) km and 5 minutes. For (b), radar location and assimilation cycle are (0, 0) and 2 minutes. For (c) and (d), radar location and assimilation cycle are (-100, 0) and 2 minutes. Spatially inhomogeneous and scanning strategy dependent error was added for experiments of (a), (b) and (c). Spatially homogeneous and scanning strategy independent error was added for experiments of (d). The black lines are for experiment assimilated PAR with 2 degrees increment observation (i.e., non-oversampling); the blue lines are for PAR with 1 degree increment (i.e., oversampling with factor of 2); the red lines are for PAR with 0.5 degrees increment (i.e., oversampling with a factor of 4); the green lines are for NEXRAD.

(3) **Using Time Balance Scheduling for Adaptive Weather Sensing**:

Since the PAR at NWRT has not had the capability of implementing the TB scheduling in real-time yet, data from the WSR-88D were interpolated to a finer time resolution to simulate the PAR observations to demonstrate and verify the scheduling algorithm. A case of multi-cell storm observed by the operational WSR-88D (KTLX) in Twin Lakes, Oklahoma from 0120 to 0300 UTC was used. The reflectivity data from four selected time periods are shown in Fig. 4 to outline the storm evolution. At 0120 UT the cell # 1 was located on the south side of the radar. At approximately 0125 UTC, the cell #2 was split from cell #1 and the scenario of two cells had lasted until 0145 UTC, when the cell #3 was formed. The cell #2 and #3 exited the radar view at approximately 0215 and 0220 UTC, respectively. Beyond 0220 UTC, only cell #1 was present. The information about number of storms and their location and size were determined by a simplified storm identification method and was provided to the scheduling algorithm.

The two quality measures of revisit improvement factor (*I*) and data acquisition (*A*) were estimated and are shown in the bottom and upper panels of Fig. 5, respectively. The revisit improvement factor is introduced to quantify the gain of the number of revisits using the adaptive sensing from conventional scan. Thus, large *I* indicates the storms being revisited more frequently compared to WSR-88D while the same data accuracy is still maintained. However, if the radar resource has been allocated mostly for sensing the storms, the surveillance task can be significantly delayed so that the newly developed storms cannot be detected. Thus, the acquisition time is introduced and defined as the minimum time for the radar to complete all required tasks at least once. For conventional scan, the acquisition time is the time radar takes to finish one volume scan. In Fig. 5, the theoretically derived improvement factor and acquisition time are denoted by dashed thick line, while the estimated ones are denoted by thin solid lines with asterisks. It is evident that before 0140 UTC and after 0210 UTC, adaptive sensing can provide fast updates (i.e., more number of revisits) on regions of storms without comprising data quality, while smaller acquisition time can be obtained (i.e., more efficiently scan the atmosphere). Note that during the period of 0140 and 0210 UTC, the radar was overloaded due to the fact that the tasks had requested radar resources more than the radar can offer. This can be mitigated by lowering the revisit time for one or more storm cells and/or incorporating prioritization of tasks into the scheduling algorithm. The benefit of adaptive sensing can be realized through the TB scheduling as demonstrated by the good agreement between the theoretical and estimated quality measures. A manuscript on this topic has been prepared and it is planned to submit it to the AMS journal in November 2009.

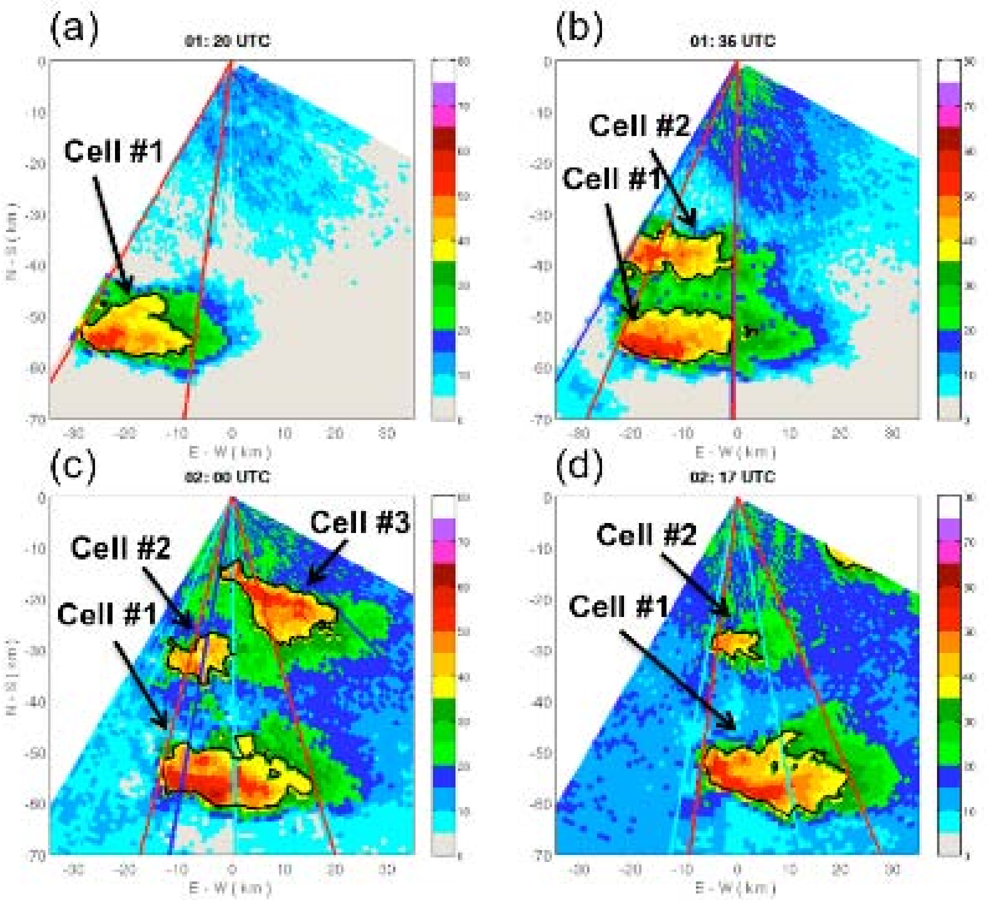

Fig. 4, Selected reflectivity fields from KTLX radar at the lowest elevation angle of 0.5^o are shown to outline the evolution of the storm cells. The TB scheduling algorithm was used to schedule up to tracking three storm cells and surveillance. The reflectivity of 35 dBZ for each storm cell is denoted by a black line. (a) only cell #1 was present within the radar view, (b) cell #2 split from cell #1 and moved to north, (c) cell #3 split from cell #2 and moved easterly. Finally, (d) shows cell #3 has left the radar view and it is not longer scheduled. In addition, the region of cells #1, #2, and #3 to be scanned by PAR in azimuth are denoted by red, blue, and cyan lines, respectively.

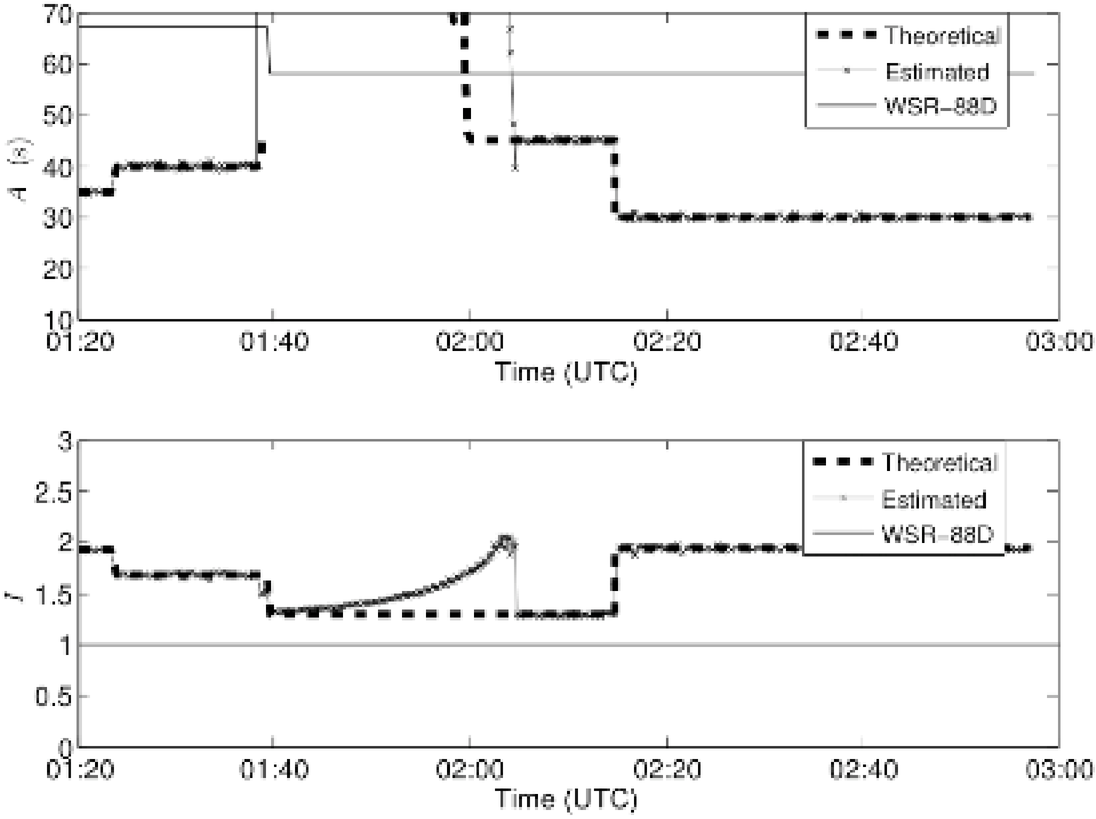

Fig. 5, The two quality measures of acquisition time and improvement factor are shown on the top and bottom panel, respectively. Good agreement between the theoretical and estimated values can be observed except for the period between 0140 and 0210 UTC, when the radar was overloaded. The results suggest that the benefit of adaptive sensing (i.e., frequent updates and low acquisition time) can be realized through the TB scheduling algorithm.

IMPACT/APPLICATIONS

Based on work in 2009, key lessons learned are listed as follows. (1) Representation of multiscale storm initiations is vital for EnKF using radar data, when mesoscale forcing plays a role in storm/convection initiation as it often happens in real world. (2) The inclusion of surface wind observations in 3 km EnKF analysis can significantly improve subsequent forecast of low level vortex structures associated with hook ech. Nevertheless, methods to use surface observation such as the observational operator need to be improved in order to be used effectively in storm scale analysis. (3) The multiscale approach provides efficient representative samples of multiscale forecast errors. (4) The present method for multiplicative and additive inflation and methods of perturbing microphysical interception need more development to further improve the performance of EnKF using real radar data with inherent multiscale complexity.

For EnKF with real data, one of the challenging issues is that the forecast storm, initiating from the analysis ensemble mean, often decays unrealistically faster than the storm in reality, even when the radar fields (reflectivity and radial velocity) from analysis match well with the ones from observations.

In this work, the multiscale complexity is highighted and a multiscale analysis procedure is designed which was used successfully in a typical dryline supercell tornadic storm. This method can be used as a framework to advance EnKF using radar data including PAR data. This work also cautions that the representation of storm/convection initiation processes when radar observation is not available is important and will strongly affect the performance of EnKF using radar data.

The modification of error model to be spatially inhomogeneous and scanning strategy dependent produce real-life statstical error in radar observations and lays a foundation to exploit adatpive weather sesning. The lessons learned from OSSE can be used to guide the design of adaptive sensing strategies in terms of update time, oversampling, and other PAR capabilities. Furthermore, the TB-based scheduling algorithm is needed to optimally allocate radar resources to perform these adaptive tasks.

RELATED PROJECTS

There is no related DoD project.

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